CONTAMINATION AND HEAT TRANSFER PROBLEMS RESULTING FROM HIGH EXPANSION OF THE SUBSONIC BOUNDARY LAYER FLOW IN THE VOYAGER TE-M-364-4 SOLID ROCKET MOTOR*

Charles J. Leising
Morris L. Greenfield

ABSTRACT

Mass and volumetric constraints dictated that the Voyager Spacecraft science instrument package be located within 40 cm of the TE-M-364-4 Solid Motor exit plane. Although the science was located 100 degrees away from the nozzle centerline, there was still concern about the flow from the subsonic boundary layer overheating and contaminating the instrument surfaces. Preliminary estimates indicated that plume shields would have to be employed, but additional information was required for design. One of the more difficult problems was how to estimate the mass flux. Standard Method of Characteristic solutions are not valid at larger angles and scaled MOLSINK test data seemed to indicate unacceptably high levels. The buildup of flow along the plume shield surface and the amount that would flow around the edge of the shield and impinge on the instruments also had to be calculated. For this latter problem TRW was contracted to use their Monte Carlo program. Confirmation was then obtained with plume instrumentation during the first Block V launch. This paper discusses the plume model, applicable MOLSINK test results, the TRW predictions and the Block V and Voyager flight results.

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1.0 DESCRIPTION OF VOYAGER PLUME IMPINGEMENT PROBLEM

To reduce structural mass and remain within a specified envelope inside the Centaur Shroud, the Voyager TE-M-364-4 75.6 kN thrust solid rocket motor was positioned with its exit plane within 40 centimeters of the science instrument package. Even though the science was located 100 degrees away from the nozzle centerline there was still concern that flow from the low velocity boundary layer in the nozzle would expand around the lip, flow backward and overheat or contaminate the instrument surfaces (Fig. 1). The Prandtl Meyer angle for low mach number flow can exceed 150 degrees.

Techniques have been developed to account for the expansion of the supersonic boundary layer but very little has been done to characterize the adjacent subsonic portion. One reason is the lack of valid analytical tools. Streamtube or Monte Carlo techniques could have been used to evaluate the Voyager configuration but no software was available. Hand calculations would have been too tedious and costly, and full scale test data was out of the question because of the cost of the solid rocket motors and the high vacuum requirements. In addition, no applicable flight data could be located.

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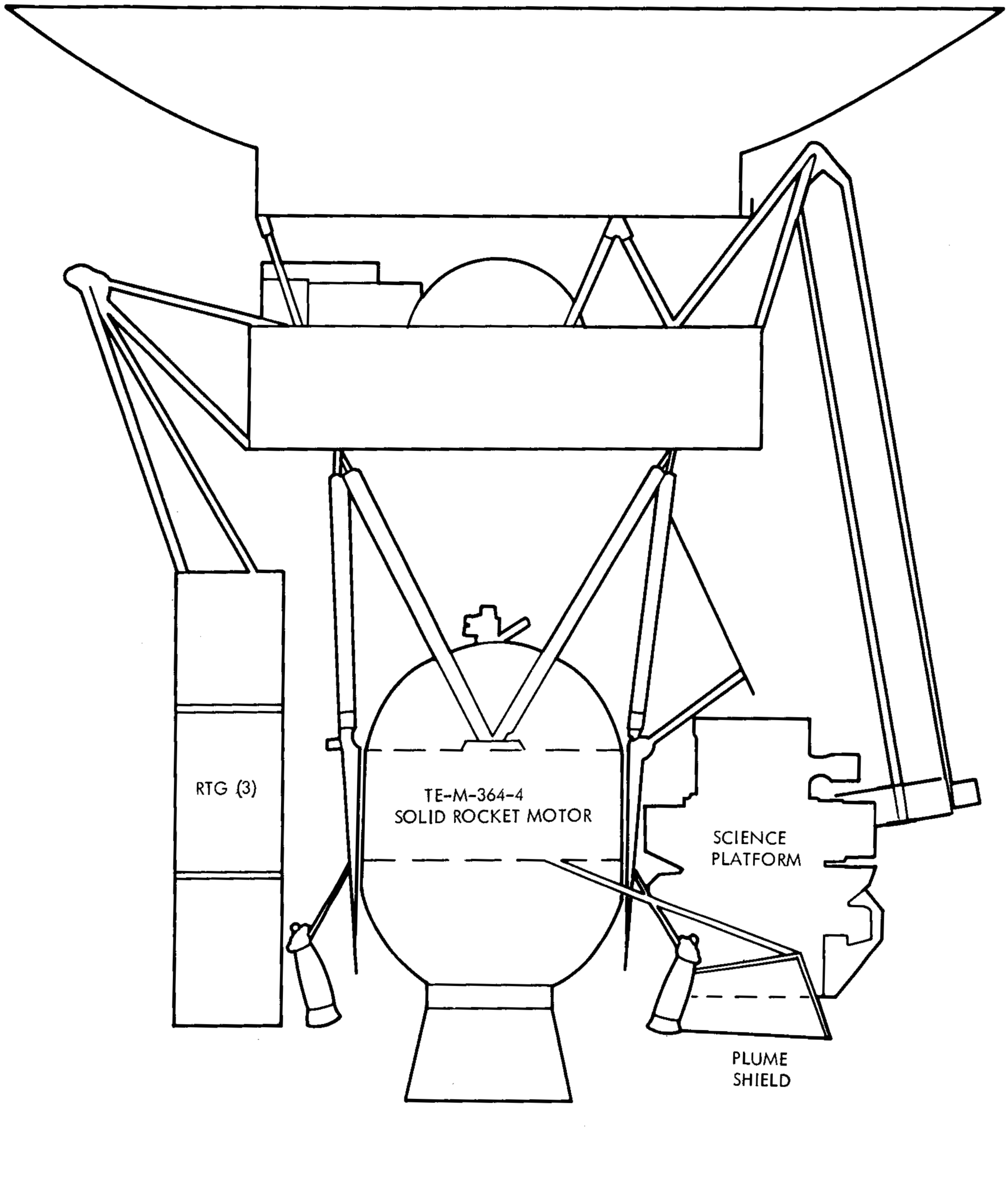


Figure 1. Voyager Spacecraft Prior to Deployment

2.0 APPROACH

2.1 Original Predictions

In spite of the difficulties some estimates had to be made. The core flow was calculated using the McDonald Douglas CONTAM program and the boundary layer flow calculated using JPL's Back and Cuffel model. The results of the latter indicated that at the nozzle exit the boundary layer was about two centimeters thick. It included both subsonic and supersonic sublayers.

In order to expand the plume the subsonic portion of the boundary layer was replaced by a uniform, sonic boundary layer with equivalent momentum flux. This is the technique that has been used by Hughes Aircraft Company. The composite plume was then expanded with the Lockheed Method of Characteristics Program. This approach should simulate the supersonic boundary layer fairly well but does not model expansion of the subsonic boundary layer. A significant uncertainty remains in the plume that originates from the subsonic boundary layer. For the TE-M-364-4 motor this flow regime begins approximately 100 degrees from the nozzle centerline. Unfortunately this is where the science platform is located.

For design purposes it was assumed that beyond 100 degrees the exponentially decreasing mass flux levels out (Figs. 2 and 3). Early data collected from a series of 0.44 N thruster tests in JPL's high vacuum MOLSINK facility also indicated a plateau but it occurred 30 degrees beyond the supersonic-subsonic boundary line. Although such a plateau could occur at high angles when widely spaced molecules collide in a random manner with the exterior surface of the nozzle, this is not considered likely. The plateau in the MOLSINK results was probably due to reflection off the cell walls. Because of uncertainty in how to interpret the test results estimates were made with a 100 degree plateau, a 130 degree plateau, and no plateau.

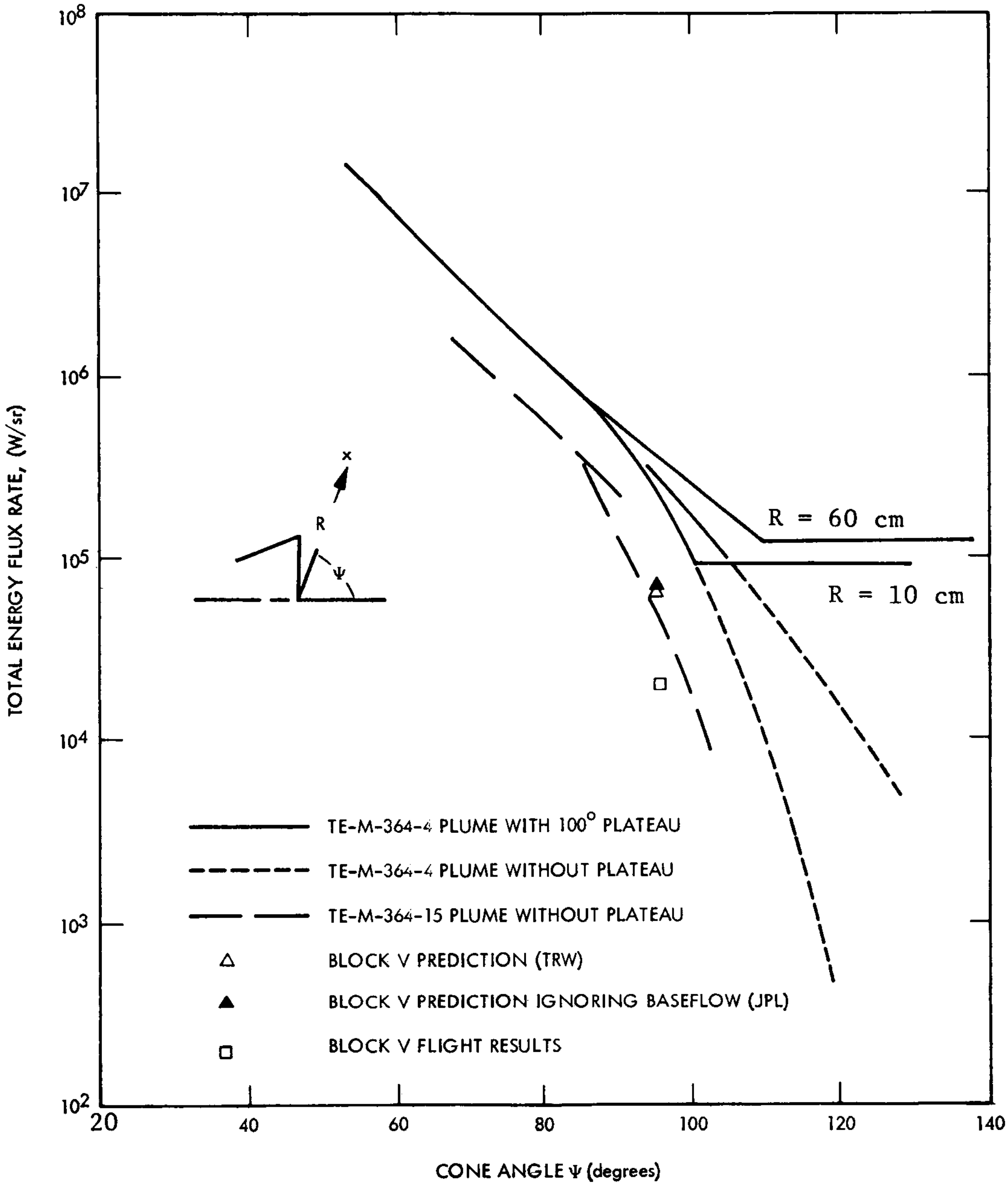


Figure 2. Energy Flux vs. Cone Angle

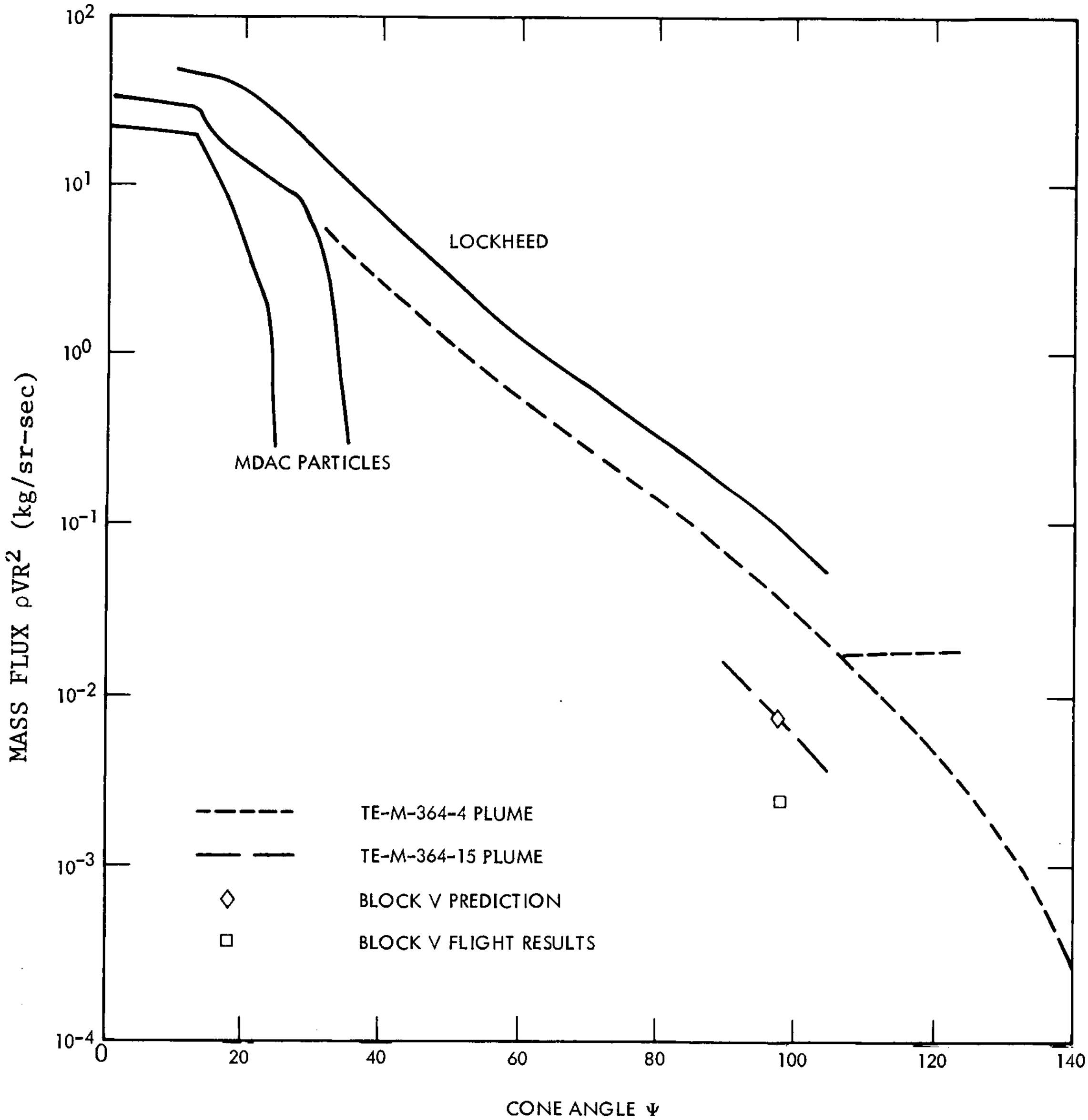


Figure 3. Mass Flux as a Function of Cone Angle

Figures 2 and 3 depict mass flux and energy flux vs. cone angle. The results indicated that energy flux on the Voyager science instrument package would approach 11.4 W/cm^2 which was far in excess of the .23 W/cm^2 allowable. Since energy flux represents only an upper limit to heat transfer more detailed heat transfer calculations were performed. Corrections were made for slip flow since the Knudsen number was calculated to equal approximately 1. The results indicated convective heat transfer rates of 1.1 to 4.5 W/cm^2 and radiative heat transfer of .11 - 1.1 W/cm^2. Mass flux was predicted to vary between 0.003 - 0.006 g/cm^2 sec. No significant particle contamination was expected since the particles would not be able to turn through the high expansion angles experienced by the boundary layer.

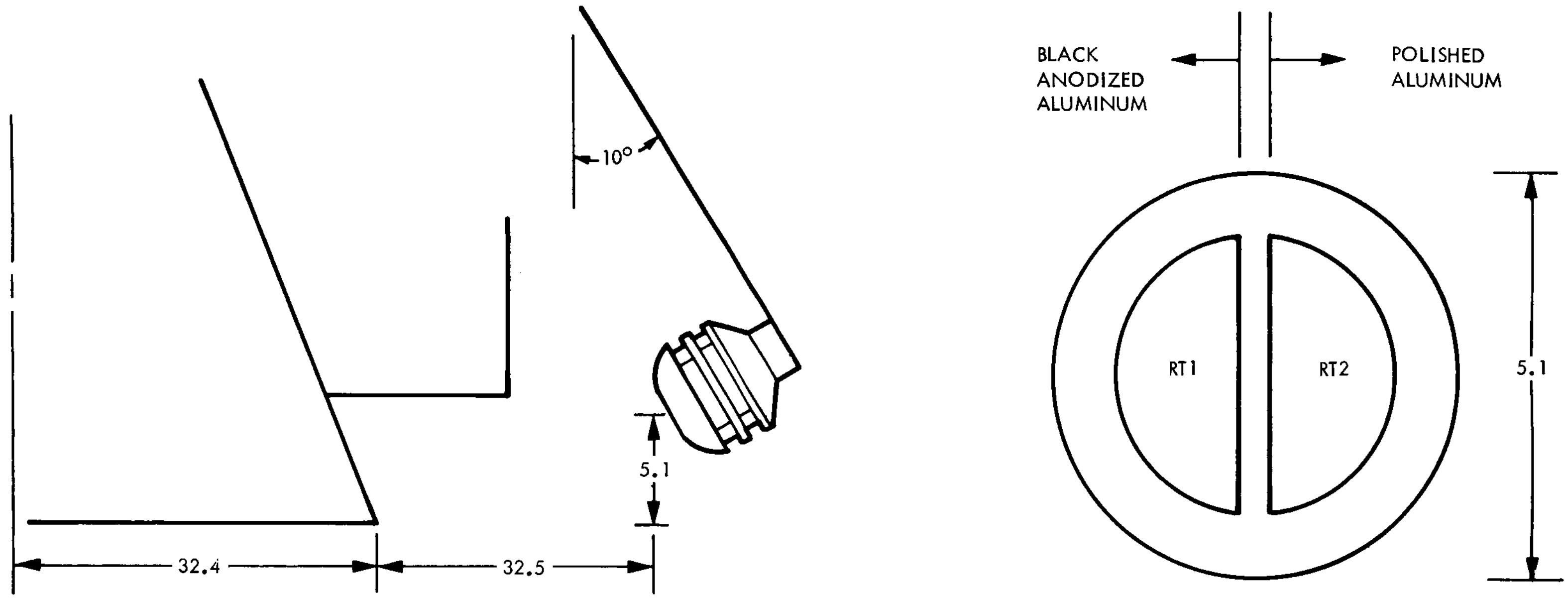
2.2 Plume Shield

To protect against potential overheating and contamination it appeared as though a plume shield would be required. However, it soon became apparent that this would be difficult to design. Additional data was required to specify thickness, location and degree of wrap-around. The shield had to be lightweight, fit within the shroud and not inhibit the science boom from later deployment. It also had to withstand the plume and prevent any significant flow around the edges. The buildup of flow along the plume shield surface and the amount that would flow around the edge of the shield had to be calculated.

The most difficult problem was calculating the buildup of flow along the shield. Approximate techniques indicated a large boundary layer 8 cm or more in thickness. This slow moving gas could turn around the edge of the shield and impinge on the science instruments.

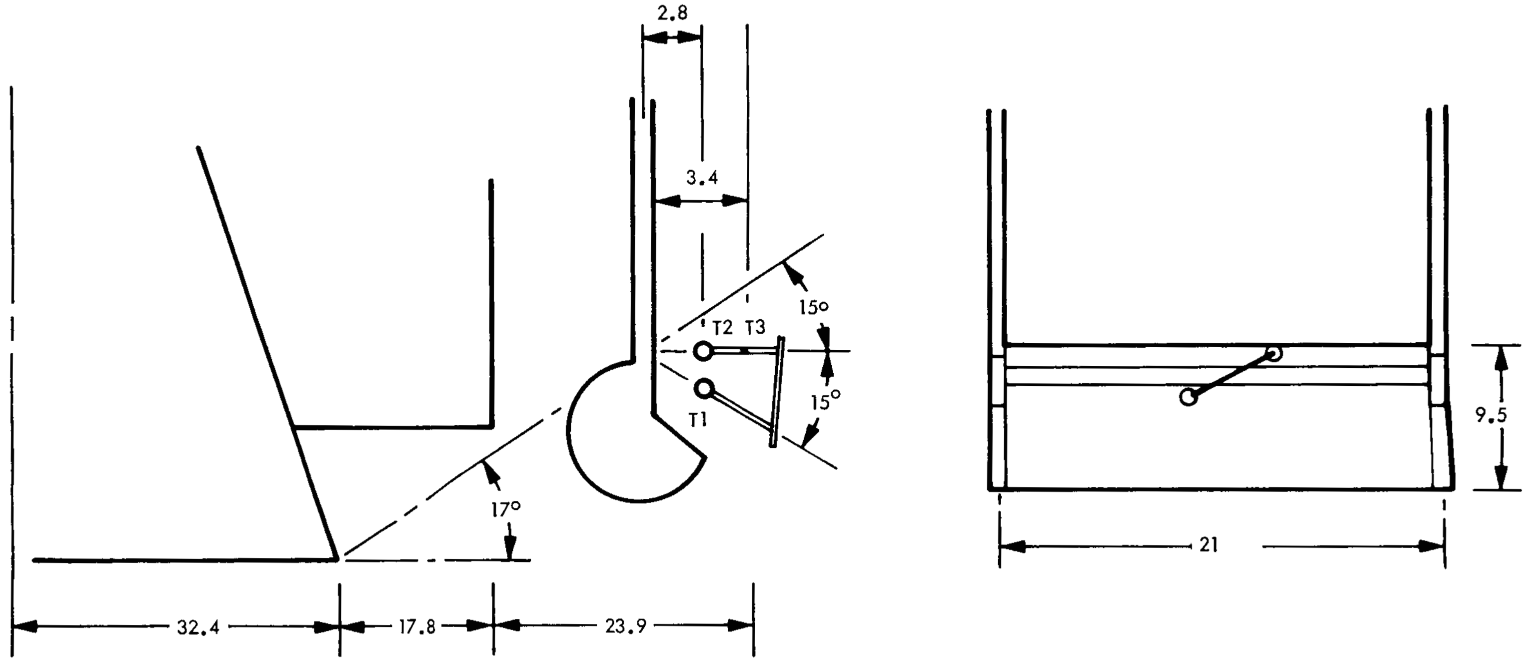
To solve this problem a contract was let with TRW to simulate the flow with their Monte Carlo program.[1] To verify these analyses calorimeters were incorporated into two plume instruments and installed next to

[1] Sugimura, T., Monte Carlo Flowfield Calculations for the MJS-77 Plume, Final Report, Contract 945381, TRW, (1977).



NOTE: ALL DIMENSIONS
IN CENTIMETERS

Figure 4. Primary Flow Block V Plume Instrument



NOTE: ALL DIMENSIONS
IN CENTIMETERS

Figure 5. Secondary Flow Block V Plume Instrument

the heat transfer to the shield, the flow around the edges of the shield and the flow impinging on the Block V instruments could all be calculated fairly well without any adjustment for baseflow. The results also indicated that flow around the edge of the shield decreased by a factor of 2.5 to 3 for every 10 degrees of turning angle (referenced from the upstream flow direction). Even at 0 degrees it appears as though there is a significant attenuation close to the shield. At no point did the predicted heat transfer behind the Voyager shield exceed the maximum allowable rate of 0.23 W/cm^2.

2.5 Correlation with Flight Results

Correlation between the Block V predictions and the flight data was good. The predicted energy flux and mass flux is presented in Figs. 2 and 3 and heat transfer predictions are summarized in Table 1. Flight results are included for comparison. Flight data are plotted in Figs. 6 and 7 and pertinent calibration data are provided in Table 2.

The energy flux was predicted to be approximately 81 W/sr or 17 W/cm^2. Based on slip flow conditions the convective heat transfer was predicted to be 2.3 W/cm^2 at RT2. As indicated in Fig. 3 these heat transfer rates correspond to a mass flux of approximately 73 kg/sec-sr or 0.003 $g/sec\text{-}cm^2$. Shielding should have reduced the mass flux at T1, T2 and T3. The convective heat transfer rates at T2 and T1 were predicted to be 0.23 W/cm^2 and 0.05 W/cm^2, respectively. Due to the flow direction, heat transfer on the stinger at T3 was expected to be negligible.

As can be observed the convective heat flux on RT1 and RT2 appears to be approximately half of what was predicted. Mass flow rate and energy flux derived from the data appear to be one-fourth of what was predicted. Considering the complexity of the model this is good agreement. The close agreement between RT1 and RT2 indicates that radiation must be a factor of three or more below what was predicted. If there

TABLE 1

COMPARISON BETWEEN MEASURED AND PREDICTED HEAT TRANSFER
TO BLOCK V PLUME INSTRUMENTS

Location	Actual W/cm^2	Predicted W/cm^2
RT 1	1.08	3.0
RT 2	1.25	2.3
T 1	0.049	0.05
T 2	0.044	0.2
T 3	0.033	0.0

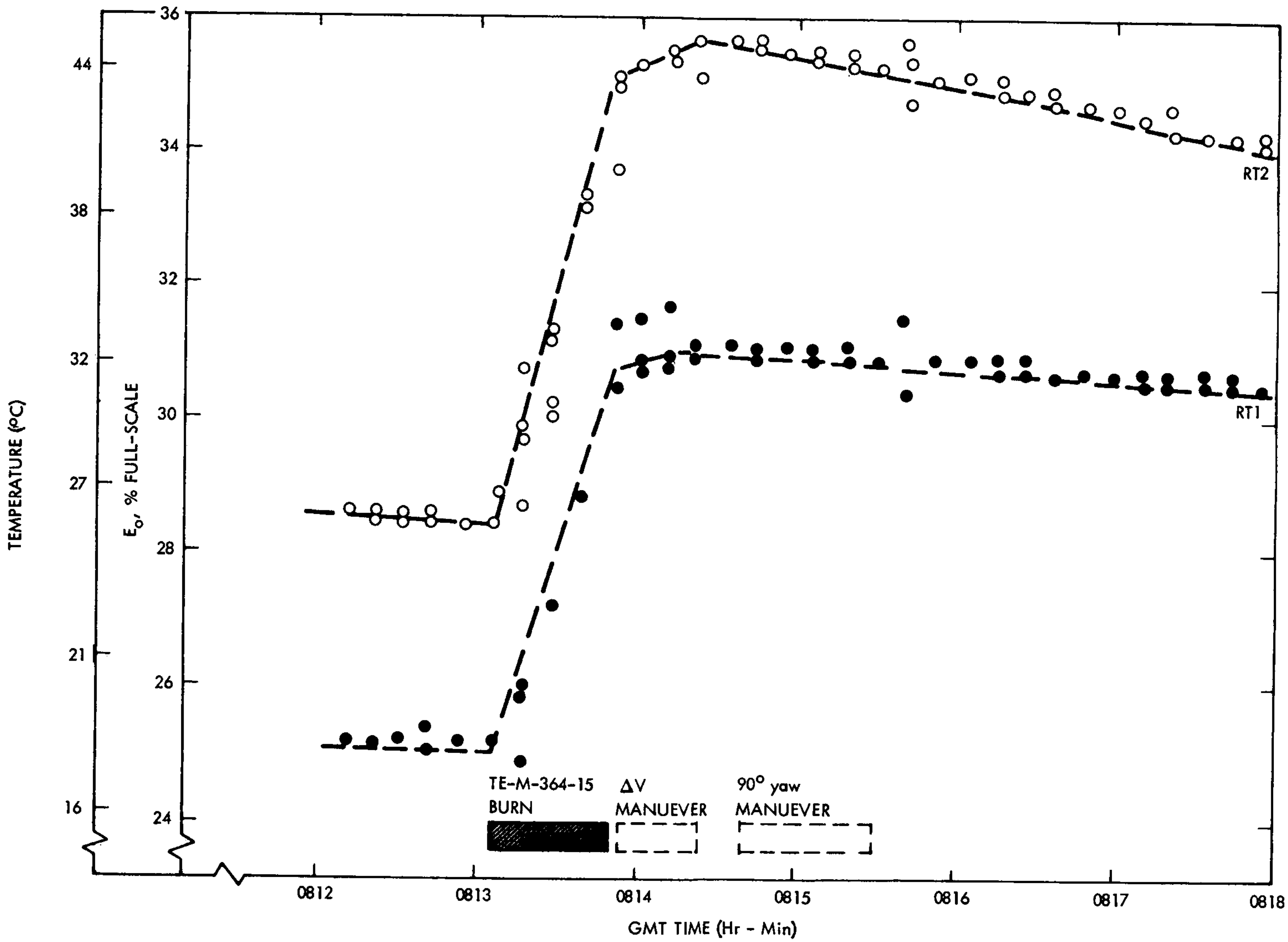


Figure 6. Block V Primary Flow Plume Instrument Data

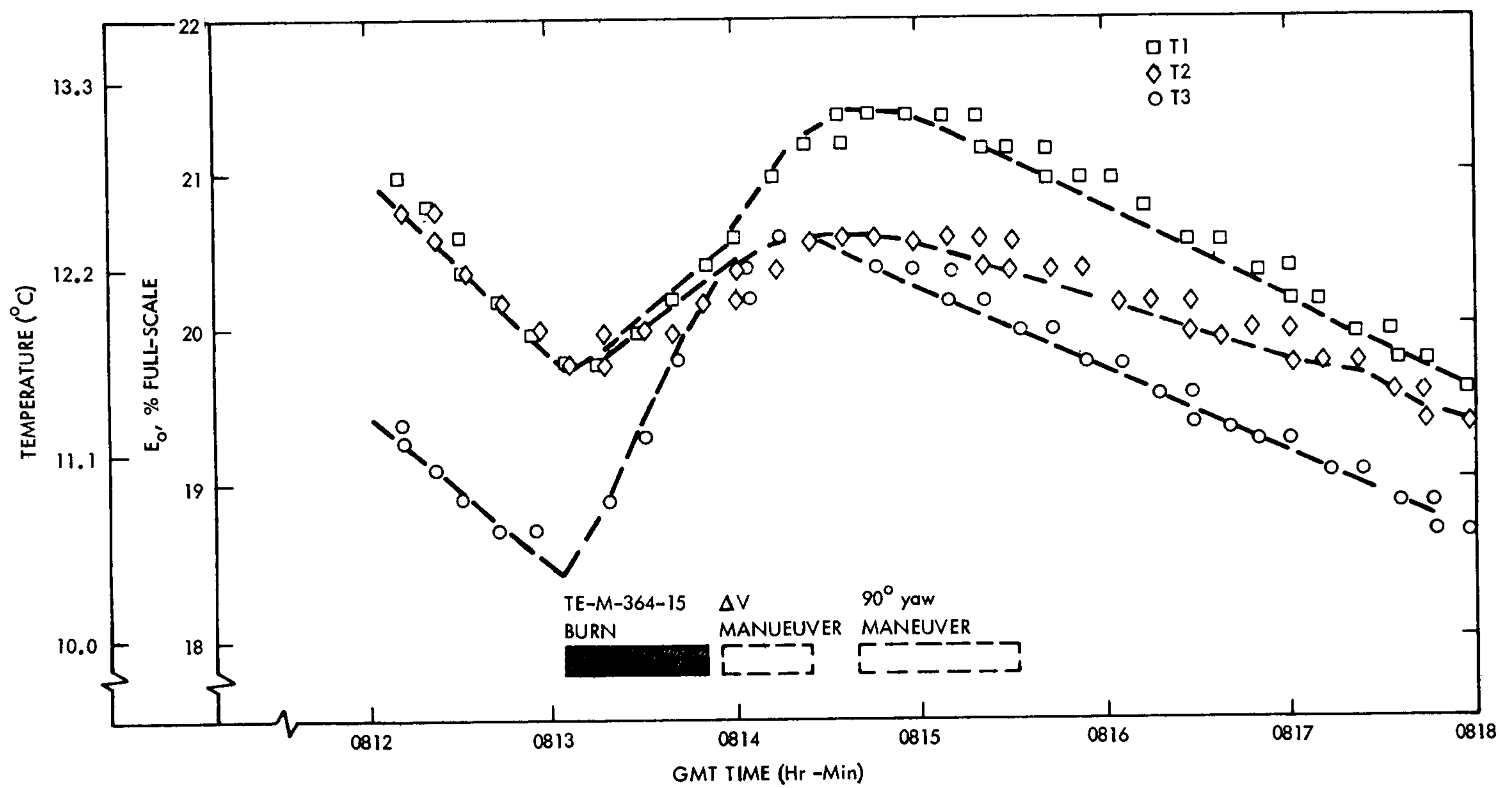


Figure 7. Block V Secondary Flow Plume Instrument Data

TABLE 2

BLOCK V PLUME INSTRUMENT DATA

Location	C $\frac{W/cm^2}{{}^{o}C/sec}$	dE_o/dT ($1^{o}C$)	$(dE_o/d\theta)_B$ (1/sec)	$(dE/d\theta)_{PB}$ (1/sec)	q W/cm^2
RT 1	3.23	0.40	0.129	-0.003	1.08
RT 2	3.23	0.40	0.149	-0.003	1.25
T 1	1.51	1.08	0.016	-0.019	0.049
T 2	1.51	1.08	0.013	-0.019	0.044
T 3	0.61	1.08	0.040	-0.018	0.033

Notes:

$$q = \frac{C}{dE_o/dT} \quad (dE_o/d\theta)_B - (dE_o/d\theta)_{PB} \qquad (1)$$

q = deduced heat transfer rate, W/cm^2

C = calorimeter constant, $W\ sec/{}^{o}C\ cm^2$

dE_o/dT = sensitivity of the signal conditioning circuit output to temperature change (in the region of interest), $1/{}^{o}C$

$dE_o/d\theta$ = measured telemetered signal change rate, 1/sec

B - during

PB - prior to burn

was any significant radiation RT1 would have measured a higher heat transfer rate than RT2, the black anodized surface of RT1 having an absorptance about three to six times greater than the polished aluminum surface on RT2. Finally the magnitude of the measurements of T1, T2 and T3 again indicate a mass flow rate approximately four times less than predicted. However, there is evidence (temperature rise rate of T3) that the flow was not aligned with the stinger axis, suggesting that there was mixing or turbulence in the flow. This could perhaps be from impingement on the instruments.

Results later obtained on Voyager confirmed that the predictions were somewhat conservative. Temperatures on the plume shield rose at only moderate rates. Because of the configuration of the temperature sensors it is difficult to assess these measurements quantitatively. No anomalous behavior or damage to the science was observed.

3.0 CONCLUSIONS

The Block V flight data indicates that there is a significant amount of mass flow at angles as large as 90^o. Calorimeters mounted 20 to 30 cm away from the TE-M-364-15, 44.5 kN Solid Rocket Motor measured a convective heat transfer rate of about 1 W/cm^2 corresponding to a mass flux of 0.00075 g/cm^2-sec. To predict these magnitudes, classical boundary layer and method of characteristic solutions can be used. On Block V the measured convection was only half of that predicted, whereas energy flux and mass flow rate were about a fourth of what was predicted. At these large angles, this is considered fairly good agreement. The largest uncertainty is probably the boundary layer thickness. Beyond the supersonic boundary layer flow regime, there is a significant uncertainty in mass flux. Although new analytical tools should be developed, it is probably acceptable in the meantime to assume that mass flux continues to decay exponentially until 30 degrees beyond the supersonic-subsonic boundary layer point.

Nothing in the flight data or analysis disapproves the existence of plateau at high angles; but both seem to indicate that there is no significant buildup of flow along the Block V base or Voyager plume shield. The efficacy of a plume shield is confirmed by the Monte Carlo analysis, the Block V experiment and by the satisfactory performance of the Voyager plume shield. Mass flux can be reduced by a factor of 2.5 to 3 for every 10 degrees of turning angle.

4.0 ACKNOWLEDGEMENTS

Appreciation is expressed to Dr. Jason Seubold, Dr. Takashi Sugimura (TRW) and Lt. William Kosman (SAMSO). Dr. Seubold was instrumental in the overall effort. He constructed the models, generated the plume predictions and assisted in defining the configuration of the Block V instruments. Dr. Sugimura was responsible for the outstanding results obtained in the Monte Carlo analysis. Lt. Kosman was JPL's prime interface with the Block V Project. He also supplied the raw flight data. Appreciation is also expressed to SAMSO, RCA and the Block V Project for their cooperation and assistance.

5.0 REFERENCE

Sugimura, T., Monte Carlo Flowfield Calculations for the MJS-77 Plume, Final Report, Contract 945381, TRW. (1977)